# Quantitative Impact of Current Harmonics on Electromagnetic Lossesi n Automotive PMSMs

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This paper investigates the quantitative impact of current harmonics on electromagnetic losses in PMSMs used in automotive applications. We compare losses generated by sine current with those produced by conventional 2-level SVPWM inverter. A dynamic model is developed to capture the interaction between the 2-level inverter and the PMSM, accurately predicting the resulting harmonic currents. These predicted currents are then used as input for a FEA to calculate the electromagnetic losses in various motor components. Our analysis reveals that current harmonics can significantly increase the total electromagnetic losses in the motor through the whole operating range.

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## I Introduction

The automotive industry prioritizes compact, lightweight, and cost-effective electric motors for propulsion systems. This trend leads to the development of low-inductance Permanent Magnet Synchronous Motors (PMSMs). However, increasing battery voltages and lower motor inductances pose a challenge: higher current ripples are generated by standard 2-level Space Vector Pulse Width Modulation (SVPWM) inverters. This raises a crucial question: how do higher harmonics in the current waveform affect electromagnetic losses in these motors compared to ideal sine current supply?

This paper presents a comprehensive analysis of electromagnetic loss breakdown in automotive PMSMs with low inductance, driven by a SVPWM inverter at supply voltages in range of 800 V. We compare the losses generated by the actual harmonic-rich current to those of an ideal sine current scenario.

A non-linear PMSM model is coupled with a SVPWM inverter model in MATLAB-Simulink to accurately predict the harmonic currents. In the next step transient two-dimensional electromagnetic analysis is performed across the motor's entire torque-speed operating range for both harmonic and sine current cases. Motor losses were categorized into the losses in the stator winding, losses in the stator and rotor core and the losses in the magnets. We thoroughly analysed and compared the generated harmonic currents and the resultant electromagnetic losses in PMSM for both current scenarios.

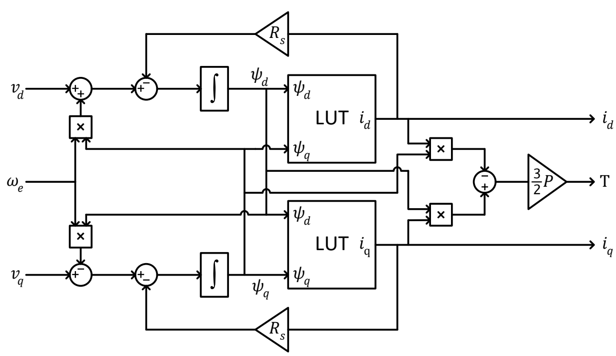


**Figure 1: Non-linear motor model**

## II Losses calculation methods

This chapter details the modelling approaches used to accurately capture the impact of harmonic currents on electromagnetic losses in PMSMs.

To comprehensively account for harmonic current effects in the stator winding, we adopted a meticulous modelling strategy. Each wire of the motor distributed winding within the stator slots is modelled as a separate conductor. Apart from calculation of Joule losses, this is enabling the consideration of additional losses due to eddy currents, skin effect and proximity effect.

While the Bertotti loss model is commonly used for stator core losses, its sensitivity to higher harmonic magnetic fields is limited. Therefore, we implemented the Loss Surface model [4], which estimates the magnetic losses *a posteriori*, based on a model of dynamic hysteresis associated to a finite elements simulation. This model requires pre-defined material properties through a characteristic surface Magnetic field strength in dependence of Magnetic flux density and Rate of change in Magnetic flux density - H(B,dB/dt), which is normally obtained experimentally.

Like the stator winding, detailed 2D geometry is employed to model the magnets. This allows for the simulation of magnet losses under harmonic current conditions.

By adopting these tailored modelling techniques, we comprehensively investigate the impact of harmonic currents on electromagnetic losses across all crucial motor components, providing a realistic assessment of motor performance under actual operating conditions.

## III PMSM loss evaluation

In PMSM stator windings, copper losses comprise DC losses arising from the magnitude of the fundamental current and the phase resistance, and AC losses dependent on the fundamental current frequency and higher harmonics. Sine current induces a 10% fluctuation in losses over one electrical period, implying a dominant DC component. Compared to sine current, harmonic current significantly amplifies copper loss fluctuations. This indicates a pronounced increase in AC losses due to higher frequency components in the current.

Stator core losses in PMSMs typically encompass hysteresis losses, classical eddy current losses induced by fundamental magnetic field changes, and excess eddy current losses caused by higher harmonic content. While the first two are primarily influenced by motor design and material properties, the presence of harmonics significantly impacts the latter category. Compared to sine current excitation, harmonic currents within the motor amplify the fluctuations of magnetic field, leading to increased eddy current losses and, consequently, elevated stator core losses.

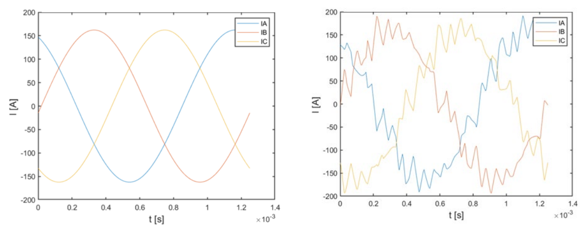


**Figure 2: Sine current (left) and harmonic current (right) at 12000 rpm and 50 Nm. THD of harmonic current is 15.9 %.**

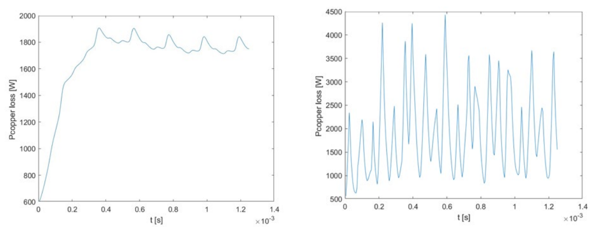


**Figure 3: Winding loss at 12000 rpm and 50 Nm. Left: With sine current. Right: With harmonic current.**

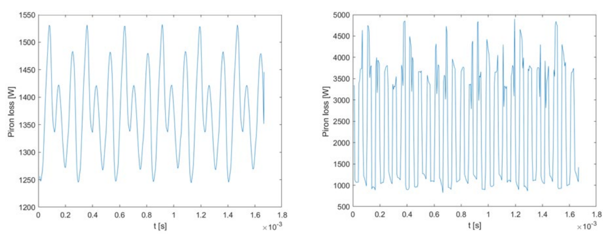


**Figure 4: Stator core loss at 9000 rpm and 150 Nm. Left: With sine current. Right: With harmonic current.**

Eddy currents are primarily contributor to losses in both the rotor core and permanent magnets. Similar to the previously discussed observations, harmonic currents significantly influence eddy current generation and therefore elevated losses in the rotor core and permanent magnets.

## IV Results and discussion

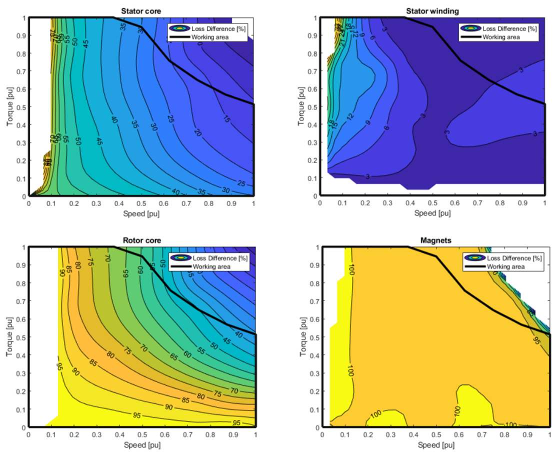


**Figure 5: Percentage of loss reduction with sinusoidal current [in %].**

Percentage of loss reduction was calculated as follows:

$$p_{lr} = ((P_{harmonic} - P_{sin})/P_{harmonic}) * 100 \quad (1)$$

Figure 5 unveils the relative difference in losses within key motor components when comparing sine and harmonic currents. We can observe that harmonic current has biggest relative influence on magnets, followed by rotor core. This suggests that current harmonics contribute significantly to losses in these components.

Since stator winding and core losses exceed rotor and magnet losses by approximately an order of magnitude, most motor efficiency gains come from lowering the losses in the stator. Regions of peak loss difference are at low-speed operation, where frequent inverter switching generates numerous current ripples over one electrical period, leading to magnified harmonic losses, and at low torque and high-speed operation, where relative importance of harmonic losses becomes more pronounced compared to total motor losses.

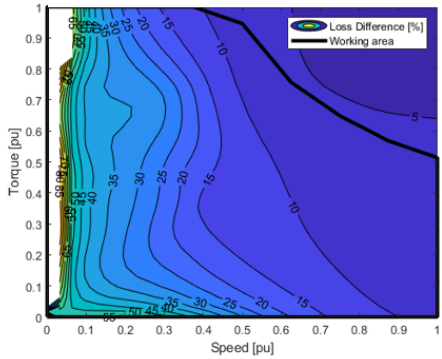


**Figure 6: Combined percentage of loss reduction with sinusoidal current [in %].**

## V Conclusions

This study highlights the crucial role of harmonics in affecting motor performance and emphasizes the need to consider them for accurate efficiency assessments. Employing SVPWM inverters in automotive Permanent Magnet Synchronous Motors (PMSMs) injects harmonic currents, leading to elevated electromagnetic losses across the whole operational range, with most influence at low speeds. The research quantifies the specific contribution of current harmonics to various motor component losses.

Future work will validate these findings through physical testing, explore advanced control techniques for mitigating harmonic currents and consequently their losses, and analyse the subsequent impact on motor thermal behaviour and overall performance.

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